Spectrally Invariant Approximation Within Atmospheric Radiative Transfer

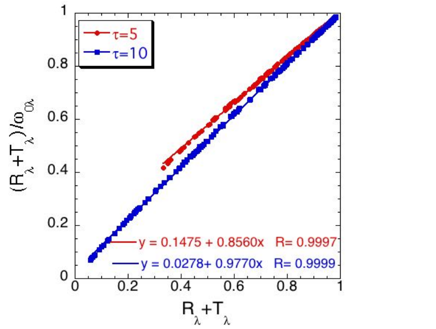
Research Highlight

The solution of the radiative transfer equation depends on its boundary conditions (solar illumination and surface reflectance) and on three independent variables—optical depth, phase function, and single scattering albedo. This study assumes that the functional dependence of the solution of the radiative transfer equation on optical depth and phase function does not change with wavelength, while the wavelength-dependence comes only from the single scattering albedo spectra. Such a separation of variables is natural for radiative transfer in leaf canopies where scattering centers are much larger than the wavelength of solar radiation. For atmospheric radiative transfer this assumption is not met, in general because the size of scattering centers (air molecules, aerosol and cloud particles) is comparable to the wavelength of solar radiation. However, in cloud-dominated atmospheres, the above assumption can be met approximately for a large range of wavelengths. This study shows that, at least for clouds with optical depth larger than 3 and wavelengths that exclude strong water-vapor-absorbing spectral intervals, the assumption holds with variations less than 5%. Consequently, the linear spectral-invariant relationships are valid (see Figure 1), i.e., the ratio of the radiative quantity (radiance or flux) to the total single scattering albedo is a linear function of this quantity; its slope and intercept are wavelength-independent.

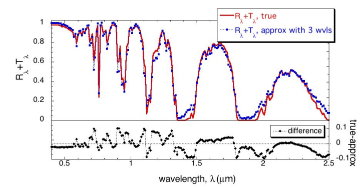
These results can be directly applied to simple radiative transfer calculations if the same radiative quantity is required for different single scattering albedos. If the single scattering albedo is known, it will also help to fill spectral gaps in the spectral observations. For climate models it is assumed that if the particle effective radius is known, the total single scattering albedo can be calculated as a function of wavelength. Using the assumptions of the spectral invariant approach, one can calculate fluxes for only a few wavelengths and obtain the two wavelength-independent variables (slope and intercept). Fluxes for all other wavelengths could be derived from these two variables and the single scattering albedo spectra. Thus, for estimating a broadband integral, a small number of radiative transfer calculations may be sufficient if high accuracy is not required. As an example, the sum of reflectance and transmittance has been approximated as a function of all shortwave wavelengths from 0.4 to 2.5 μm using radiative transfer calculations at only three wavelengths with a bias of 0.006 out of 0.53, or about 1% (see Figure 2).

If the spectral single scattering albedo is available, the slope of the linear relationship can be obtained directly from observations without any parameterizations and/or radiative transfer calculations. The product of the slope and the single scattering albedo approximates the maximum eigenvalue of the radiative transfer equation. As far as we are aware, this is the first method for estimating the maximum eigenvalue directly from atmospheric measurements.

Recently we reported a surprising spectral invariant relationship in shortwave spectrometer observations taken by the ARM Climate Research Facility. The relationship suggests that the shortwave spectrum near cloud edges can be determined by a linear combination of zenith radiance spectra of the cloudy and clear regions. We confirmed these findings with intensive radiative transfer simulations of the different aerosols and clouds properties as well as the underlying surface types and the finite field-of-view of the spectrometer. Though the calculations were performed for 1D clouds, first 3D radiative transfer results suggest that the SI relationship discovered in shortwave spectrometer measurements is valid for the 3D simulation world. A clear physical understanding of the observed and simulated SI behavior of zenith radiance around cloud edges is still missing. The current study is the first step in this direction.



Ratio of reflectance R# plus transmittance T# over single scattering albedo #0# plotted against the sum R#+T# for two cloud optical depths: 5 and 10. The aerosol optical depth at 0.55 μm is 0.2 (rural type of aerosol). Different dots correspond to different wavelengths from 0.4 to 2.5 μm with spectral resolution of 0.01 μm; only spectral intervals that exclude strong water vapor absorption are used here. Note that in the linear fits the sum of slope and intercept is 1.



Reconstruction of the sum R# + T# using the spectral invariance approximation. The slope is obtained from only three wavelengths: 0.4 μm, 1.6 μm, and 2.1 μm. Retrieved values for all 211 wavelengths from 0.4 to 2.5 μm are shown.

For original submission and image(s), see ARM Research Highlights
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Reference(s)

Marshak A, Y Knyazikhin, JC Chiu, and WJ Wiscombe. 2011. "Spectrally-invariant approximation within atmospheric radiative transfer." Journal of the Atmospheric Sciences, 68(12), doi:10.1175/JAS-D-11-060.1.

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Working Group(s)

Cloud-Aerosol-Precipitation Interactions